PREDICTABILITY OF THE CALIFORNIA CURRENT SYSTEM

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1. Background

The physical and biological oceanography of the Southern California Bight (SCB), a highly productive subregion of the California Current System (CCS) that extends from Point Conception, California, south to Ensenada, Mexico, continues to be extensively studied. For example, the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program has sampled this region for over 50 years, providing an unparalleled time series of physical and biological data (e.g. Chelton et al. 1982; Roemmich 1992; Hickey 1993; Roemmich and McGowan 1995; Hickey 1998). However, our understanding of what physical processes control the large-scale and mesoscale variations in these properties is incomplete (e.g., Roemmich 1989; Simpson and Lynn 1990; Bograd et al. 2001). In particular, the non-synoptic and relatively coarse spatial sampling (70km) of the hydrographic grid does not completely resolve the mesoscale eddy field (Figure 1a). Moreover, these unresolved physical variations exert a dominant influence on the evolution of the ecosystem (e.g., Hayward and Venrick 1998).

In recent years, additional datasets that partially sample the SCB have become available. Acoustic Doppler Current Profiler (ADCP) measurements, which now sample upper-ocean velocity between stations (Figure 1b; Chereskin and Trunnell 1996), and sea level observations along TOPEX tracks (Figure 1c; Kelly et al. 1998; Strub and James 1999) give a more complete picture of the mesoscale variability. However, both TOPEX and ADCP are well-sampled only along the cruise or orbit tracks and coarsely sampled in time and between tracks. Surface Lagrangian drifters also sample the region, although irregularly in time and space (Figure 1d; Poulain and Niiler 1989; Swenson and Niiler 1996).

SeaWiFS provides estimates of upper-ocean chlorophyll-a (chl-a), usually giving nearly complete coverage for weeklong intervals, depending on cloud coverage. Historical ocean color data from the Coastal Zone Color Scanner (CZCS) has been used extensively to determine phytoplankton patterns (Peláez and McGowan 1986) and variability (Smith et al. 1988), characterize the primary production across the SCB coastal fronts (Smith et al. 1987), and describe the seasonal and interannual variability in pigment concentrations (Thomas and Strub 1989, 1990). As in CalCOFI, these studies described much of the observed structures and their variability over relatively large space and time scales.

The field and satellite data have not been widely used to examine the short-term evolution of features, e.g., within the time span of a single CalCOFI cruise. With the advent of many new techniques for obtaining quasi-synoptic, high space and time resolution observations (e.g., CODAR estimates of surface currents, drifter platforms for salinity, atmospheric pressure and biological measurements, subsurface glider measurements of the upper ocean, etc.), it is of great importance now to develop procedures that can make use of this combined suite of observations to synthesize a complete picture of coupled physical-biological activity.

Many different ocean circulation modeling studies have attempted to reproduce the mean and seasonal structure of the California Current (e.g., Philander and Yoon 1982; McCreary et al. 1992; Oey, 1999), its instabilities (e.g., Batteen et al. 1989; Auad et al. 1991; Haidvogel et al. 1991; Allen et al. 1991; Hurlburt et al. 1992; Batteen and Vance 1998; Marchesiello et al. 2001) and both its locally and remotely forced interannual variations (e.g., Pares-Sierra and O'Brien 1989; Ramp et al. 1997; Miller et al. 1997). A coupled ecosystem-circulation model was also developed and implemented for the Coastal Transition Zone, a more physically and biologically dynamic region of the CCS, but with similar ecosystem processes (Moisan and Hofmann 1996a; Moisan et al. 1996). However, few attempts have been made to reproduce the time history of the temperature and current structure in detail (see Robinson et al., 1984, and Rienecker et al., 1987, for noteworthy exceptions).

The novel idea here is to use a circulation model and all the data obtained during a single CalCOFI survey to reproduce the time evolving circulation field during an individual CalCOFI survey. The resulting eddy-resolving model attempts to match observations to within observational error over the time interval during which the data were obtained and would be used to drive an ecosystem model. The results from this model can then be used to definitively analyze both the circulation and ecosystem dynamics of the Point Conception Upwelling System for the first time. The fit between the model and the available data sets provides a quantitative test of the model quality and can be used to point out possible ways to improve the model.

If a physical-biological model of the SCB can successfully synthesize the data, specific scientific questions can be addressed.

(1) What physical and biological processes control the large-scale and mesoscale features observed in the CalCOFI region?

(2) How do the processes that control the time development of the phytoplankton field vary seasonally and annually?

(3) What are the predictive timescales of the physical and ecosystem variables as a function of region (shelf-slope, upper-ocean, deep-ocean thermocline), generating mechanism (atmospheric forcing, intrinsic variability) and data density?

The focus of this project was to use the available remotely sensed ocean color data to quantify the biological scales of variability which have not been resolved in CalCOFI or other studies. To achieve this goal, we collected additional data and developed techniques to analyze the new and existing CalCOFI physical, chemical, biological and bio-optical data and available remotely sensed data (ocean color, SST, wind, currents, sea surface height). The study involved the development of an eddy-resolving numerical model of the California Current System (CCS) that synthesized these diverse data types to allow the diagnosis (hindcasting) and forecasting of biological and physical ocean variables.

2. Overview of Research Results

Our work during the past years focused on (i) dataset assembly and analysis (including hydrography, ADCP, altimetry, drifters, ocean color, atmospheric forcing, etc.), (ii) dynamical model implementation and testing, (iii) data fitting/inverse method testing, and (iv) ecosystem model development, implementation, and testing.

During the first year of funding, the 1997-98 El Niño began to develop and funding was provided (as a supplement to our grant) to Dr. Janet Sprintall and Prof. Dan Rudnick to measure hydrography several times between the usual quarterly CalCOFI surveys. Together with the extra mini-CalCOFI sampling, this yielded approximately monthly sampling (albeit with fewer transects than the regular CalCOFI surveys) from 11/97 until 2/99. This required additional work by us in data acquisition and quality control. Additionally, special releases of drifters were executed and prepared for use in the assimilation.

Hydrographic and other data were processed into a form suitable for use in smoothly initializing the ocean model and for evaluating model-data mismatches. A dataset was assembled that spans the last 15 years, corresponding to the period when quarterly CalCOFI sampling began in the SCB region up to the present. A box inverse model was used to examine the low-frequency (seasonal, interannual, and ENSO) variability in flux convergences of heat, salt, nutrients, oxygen, and chl-*a* into a control volume defined by the outermost CalCOFI lines, as described by Bograd, et al. (2001). We recently also assembled a 50-year

CalCOFI dataset suitable for adaption as boundary conditions for multi-decadal ocean model simulations of the flows in the southern CCS.

Drifters were used to quantify wind-driven Ekman current energetics. All of the available CCS drifter data was analyzed and the Ekman current model of Ralph and Niiler (1999) was shown to apply to the CCS latitudes as well (Niiler and Barth 2000).

The following publications were a direct result of this funded proposal:

Bograd, S. J., T. K. Chereskin, and D. Roemmich, 2001: Transport of mass, heat, salt and nutrients in the California Current System: Annual cycle and interannual variability. *J. Geophys. Res.*, **106**, 9255-9276.

Di Lorenzo, E., 2002: Seasonal Dynamics of the Surface Circulation in the Southern California Current System. *Deep-Sea Res., sub judice.*

Di Lorenzo, E., A. J. Miller, D. J. Neilson, B. D. Cornuelle and J. R. Moisan, 2001: Modeling observed California Current mesoscale eddies and the ecosystem response. *Int. J. Remote Sens.*, accepted pending minor revisions.

Miller, A. J., E. Di Lorenzo, D. J. Neilson, B. D. Cornuelle and J. R. Moisan, 2000: Modeling CalCOFI observations during El Niño: Fitting physics and biology. *Calif. Coop. Oceanic Fish. Invest. Rep.*, **41** 87-97.

Niiler, P. P., and N. Barth, 2000: Annual mean circulation and eddy variability in the Eastern North Pacific. In: *Oceanography of the Eastern Pacific*, Farber-Lorda, J. and Echavarria-Heras, H., eds., 5-22.

The funding from this grant provided the basic support for the Ph.D. dissertation research for Mr. Emanuele Di Lorenzo in the Climate Sciences curriculum at Scripps. He intends to defend in early 2003, and his thesis will consist of the papers listed herein with him as first author as well as others in preparation.

The funding of this grant was also the primary motivation for a successful workshop co-hosted by Scripps and UCLA entitled "California Current Modeling: Do Observations Corroborate the Modeled Phenomena?" during February, 1999. The First Scripps Surfside Climate Workshop brought together scientists who model the California Current System with those who observe the system in order to critically assess the ability of ocean models to simulate the observed synoptic phenomena. Invited presentations were followed by extensive discussions to help identify the major accomplishments, deficiencies and challenges in the present state of California Current modeling as summarized by Miller et al. (1999).

Miller, A. J., J. C. McWilliams, N. Schneider, J. S. Allen, J. A. Barth, R. C. Beardsley, F. P. Chavez, T. K. Chereskin, C. A. Edwards, R. L. Haney, K. A. Kelly, J. C. Kindle, L. N. Ly, J. R. Moisan, M. A. Noble, P. P. Niiler, L. Y. Oey, F. B. Schwing, R. K. Shearman, and M. S. Swenson, 1999. Observing and modeling the California Current System. *Eos, Transactions, American Geophysical Union,* **80**, 533-539.

We also developed an Ocean State Estimation Projects web page *http://ono.ucsd.edu* to disseminate both the physical and ecosystem modeling results of this and related projects.

Our work was also presented at a large number of national and international scientific conferences including the Oceans from Space Symposium, Venice, Italy, 9-13 October 2000, where our poster entitled "Modeling California Currenst mesoscale observations: Fitting physics and biology" won a **poster award** (*http://ono.ucsd.edu/index.cgi?calcofimeso*).

3. Detailed Description of CalCOFI Modeling Results

In order to better interpret the dynamical balances of the physical and biological fields of the SCB, we attempted to use an ocean model to merge together the various data types and develop a complete four-dimensional picture of the evolving flow field and its biology during an individual cruise. This model-testing procedure takes the form of a least-squares fit. If the fit is determined to be successful, and the data are sufficient, the model run can be used to assess the balances that control the evolving phenomena. If not, the model must be corrected or discarded. The final test of the model quality is to run the model beyond the fitting time interval into a forecast time interval and quantify the model skill by comparing against independent data.

Surveys of temperature, salinity, and velocity from CalCOFI, altimetric measurements of sea level, and drifter observations of temperature and velocity during the 1997-98 El Niño were fit with an eddy-resolving ocean model of the SCB to obtain dynamically consistent estimates of eddy variability. The physical fields were then used to drive a 3D NPZD-type model in attempts to fit NO_3, chl-a and bulk zooplankton data from the CalCOFI surveys and integrated chl-a values from SeaWiFS.

This research focused on investigating several fundamental scientific issues such as the nature of mesoscale instabilities, topographic control, remote oceanic forcing and wind forcing in eddy evolution in the CalCOFI region; the relative predictive time scales of deep ocean, surface and shelf-slope processes; and role of various ecosystem processes in SCB carbon budget. Below we present our results in fitting hydrography, tuning of the 1D mixed-layer/ecosystem model parameters based on historical CalCOFI data, and initializing 3D ecosystem structure from data.

3.1 Data Sources

CalCOFI hydrographic data (*http://www-mlrg.ucsd.edu/calcofi.html*) from 1949–1999 were used for comparing against model results, and for creating first-guess initial and key background nudging conditions. The data used for various purposes include: temperature, salinity, density, oxygen, NO_3, chl-a, and primary production rates.

Climatological profiles of the data were created by binning the offshore and coastal stations. Further analysis of the CalCOFI data included objective analysis (OA) to create maps of the data fields at model levels for first-guess initial conditions (IC). Original hydrographic measurements were used for quantifying fitting skill. ADCP velocity estimates were created using one-hour averages which provide roughly five samples between CalCOFI hydrographic stations. TOPEX altimetric measurements of sea level were used as differences between nine-day repeat track times in order to remove geoid effects. Drifters provided daily surface velocity and temperature estimates. Atmospheric forcing was derived from COADS and NCEP/NCAR reanalysis fields.

Daily satellite-derived estimates of integrated chl-a were obtained from the NASA SeaWiFS data archive. We use the global gridded L3m SMI data set which has 9 km resolution near the equator. The satellite began collecting data in September 1997 and at present we have 3 years of images. The individual daily images are sometimes poorly resolved in the CalCOFI region due to the high fraction of cloud cover. Therefore, 5-day composites were created for use in developing IC and quantification of model-data mismatch. In addition to the SeaWiFS and TOPEX satellite data sets, weekly composite AVHRR SST data were also collected, although they are at a much lower spatial (20 km) and temporal (weekly) resolution than the SeaWiFS data.

3.2 Physical and Ecosystem Models

We used an eddy-resolving primitive equation (PE) generalized sigma-coordinate ocean circulation model called the Regional Ocean Modeling System (ROMS), which is a descendent of SCRUM (Song and Haidvogel 1994). The 9-km model grid is curvilinear and extends about 1200 km along the coast from northern Baja to north of the San Francisco Bay area with roughly 700 km offshore extent normal to the coast (Figure 1d). The northern, southern and western boundaries are treated as open boundaries by using a modified Orlanski radiation scheme with nudging to specified time-dependent temperature and salinity from a CalCOFI climatology blended with Levitus. The bathymetry is obtained from ETOPO-5 (Figure 1d) and a coastline is included via masking along the eastern boundary. In the vertical, 20 layers reach from the free surface to the bottom of the ocean. The sigma layers have increased resolution in the surface and bottom boundary layers.

The physical model was initially tested with simple external forcing and bathymetry, in order to verify its ability to capture the basic physics of the region. Integration with smooth climatological forcing (COADS and NCEP data) and with dwonscaled NCEP forcing showed that the downscaled forcing results in a far better simulation of the flows than the coarse wind forcing. This is mainly due to the better representation of wind stress in the SCB region for the downscaled winds. Di Lorenzo (2002) described these results and shows that statistics of the model are comparable with observations. Some of these features include a meandering current flowing from north to south, a poleward undercurrent on the continental slope, and a recirculation gyre in the SCB. Figure 2 shows a schematic depiction of the dynamics controlling the seasonal variability in the SCB. A more quantitative measure of the model's skill was assessed by the fitting procedure described below.

The physical model drives the ecosystem model (which can have different levels of complexity). The simulated flow fields from the 3D physical model are used to advect the ecosystem constituents. Sinking of the biological constituents is handled explicitly within the ecosystem routines. The models are presently coupled via the physics to the ecosystem model, but an option for a feedback into the buoyancy flux is available via the light absorption/attenuation routine in the ecosystem model. The basic 7-component ecosystem model components include: NO_3, NH_4, large and small detritus, phytoplankton, chl-a, and zooplankton. The present model is similar in structure to the ocean circulation ecosystem model developed and applied to the California Coastal Transition Zone by Moisan et al. (1996).

3.3 Inverse Method Fitting Technique

Many techniques exist for combining data with models (e.g., Ghil and Malanotte-Rizzoli 1991; Bennett 1992; Wunsch 1996; Lermusiaux and Robinson 1999). Least-squares methods are widely used for fitting both steady and unsteady models to data, and can be implemented sequentially as the Kalman smoother, or globally by solving the Euler-Lagrange equations to find the minimum of an objective function (Le Dimet and Talagrand 1986; Wunsch 1988; Thacker 1989; Tziperman and Thacker 1989; Bennett and Thorburn 1992). The objective function is a sum of quadratic terms penalizing misfit between the observations and the data produced by the model, and also penalizing corrections to the assumed model parameters, including forcing, IC and boundary conditions. The weighting of the penalty terms may include smoothness criteria, and the unknown forcing can compensate for errors in the model equations at every point in space and time (Bennett and Thorburn 1992). A global inverse method similar to the "Green's function method" (Wunsch 1996) was used to fit the regional PE model to the data during a CalCOFI survey covering about 3 weeks by adjusting the initial state of the model. Because the forcing and boundary conditions were not adjusted, the model evolution depended only on IC.

The starting guess for the model's IC comes from a time-independent, 3D OA of the CalCOFI observations, treating them as if they were simultaneous at the start of the survey. The model is run from this poorly-resolved initialization and the results are directly compared to the observations from the CalCOFI survey.

The misfits between the model and observations were corrected by adjusting the IC based on Green's functions that related changes in the model's IC to changes in the model estimates of the observations. The model's initial state was adjusted to minimize the sum of the squared, normalized misfits between the observations and the model predictions, while also minimizing the sum of squares of the normalized changes to the model IC. The changes to the IC were expanded with sinusoids in the horizontal and smooth functions (EOFs) in the vertical, so the minimization procedure included smoothness constraints by penalizing short length scales more than long scales. The assimilation retains the form of objective mapping as a least-squares fit (Davis 1985), with the data covariance matrix derived from the time-dependent Green's functions and the model parameter covariance. The model covariance controls the smoothing constraints, and the data error covariance governs the data fit.

Errors in fitting to the data were assumed to come from errors in the observations and from model representation errors (due to the linearization, the limited set of initial perturbations, and the limited horizontal and vertical resolution). These assumed data error bars were checked for consistency against the final misfits ("residuals"). Because advection is important in this example, the linear Green's functions depend on the initial state, so the estimation procedure must be iterated. Miller and Cornuelle (1999) and Cornuelle et al. (2000) provide further details of the fitting procedure in the context of a different oceanographic region.

3.4 Dynamical Fits

The fitting procedure was applied for the July 1997, the February 1998 and the July 1998 CalCOFI surveys. These were times when the region swung from strong El Niño conditions to strong La Ninña conditions (Lynn et al., 1998; Bograd and Lynn, 2001).

Initialization Procedure and Forcing: Prior to beginning the model fitting, an initial ocean state must be constructed to be as close as possible to the actual poorly observed one. Observations for the non-synoptic 3D temperature and salinity fields are available only in the small 'CalCOFI subdomain'. Further data (Leetmaa Pacific Ocean Analysis provided by the Climate Diagnostics Center *http://www.cdc.noaa.gov/cdc/data.leetmaa.html*) are used to smoothly fill in the ocean initial state outside this region. The model's initial velocity field was estimated by assuming it was nearly geostrophically balanced with the horizontal density gradients. Forcing fields were obtained from several different wind stress products including COADS, NCEP and scatterometer winds.

Basis Functions for Assessing Sensitivity: As described in the inverse method section, we project the error field between model and observed IC onto a reduced space. The optimal basis to be chosen for this projection is not known so we arbitrarily picked the Fourier basis sets of sines and cosines for horizontal structures as a first try. In the vertical, we use empirical orthogonal functions (EOFs) of the difference between CalCOFI observations and model-derived temperature and salinity profiles from the base run from first-guess IC. These vertical modes tend to show maximal variability at roughly 100 m, with about 70% of the variance explained by the first EOF and 20% by the second.

Initial tests of the model sensitivity to slight changes in the IC using these basis functions showed strong nonlinearities in the upper ocean (Miller et al., 2000). That is, a large-scale, small-amplitude perturbation in temperature or salinity resulted in a time-dependent perturbation from the base run that had large amplitudes at the grid scale after only a few days. The nonlinearity was traced to the KPP mixed layer parameterization (Large et al. 1994) which gives a time and space dependent vertical diffusion coefficient based on a number of criteria. Since this strong nonlinearity would complicate the linear fitting procedure, the vertical diffusion was set to a constant value that was chosen to yield reasonable mean and eddy variance states. We will address the surface-forced mixed layer process in this proposed work, and will re-examine it in the context of the linear inverse.

Results of Inverse Solutions for Observations: A total of 500 perturbation runs were typically made for temperature and salinity, resolving up to six wavenumbers in the each horizontal direction and three vertical modes. Each model run is sampled in time as the CalCOFI cruise sampled the real ocean. Each perturbation run is a model forecast for the cruise from a slightly different initial state.

In the application of the inverse, an rms fitting error needs to be assigned to each datum. The error includes both observational and representational error, which comes from the inability of the model to reproduce all the physical processes seen in the data (e.g. internal waves). The first fitting attempt used a constant rms-error-bound for each observation. However, the results tended to place more emphasis on fitting the coastal station data where the mismatch is highest. Since slow open-ocean eddies are better resolved by model physics than fast shallow-water coastal eddies, later fitting attempts allowed a larger fitting error in the coastal region than offshore. Typical error variance reductions of 70% were obtained after one iteration of the inverse with this procedure and reasonable fits of the offshore eddies were achieved (Miller et al., 2000; Di Lorenzo et al., 2002).

Time-dependent maps of sea level from the model run were constructed from the corrected initial states for the CalCOFI cruises. The slow evolution of the larger mesoscale eddies offshore and the more rapid evolution of the smaller eddies nearshore suggests that the likelihood of skillfully fitting the offshore thermocline eddies is greater than for the near-coastal squirts and jets with the available data set. More highly resolved observations in space and time will be needed for near-coastal fits. Likewise, processes in the surface mixed layer are not modeled with great skill because time-dependent surface forcing is not included and because of the limited oceanographic data.

Results of Inverse Solutions for Identical Twin Experiments: Several issues of fitting were addressed in identical twin experiments in which a model run was used to create synthetic data that is sampled and treated like observations. The relative importance of using hydrographic data and TOPEX altimetry was assessed in these fits. Fits using only sea level or only hydrography approached but did not rapidly converge on the true initial state after one or two inverses. Using the two data types together yielded more promising results on convergence to the true initial state. However, smaller-scale structures that are not sampled by either sampling scheme were not able to be accounted for by the inverse solution. The inverse solution was only able to reconstruct the well-sampled larger-scale features of the eddy field, not the smaller scale eddies. These larger scale features were, however, dynamically important because they produced realistic large-scale flow fields which have predictive skill at leads of several months (as discussed next for real observations). The use of tailored basis functions instead of sines and cosines was also explored in this framework, but none were deemed superior to the simpler basis functions.

Results of Initial Retrospective Forecasts: Retrospective forecasts were tested in a preliminary way using fits of February 1998 and July 1998 CalCOFI surveys. The skill of these forecasts was assessed as rms error for the full 3D temperature or salinity field in the CalCOFI area of the region based on observations from the following CalCOFI surveys (March and April, 1998, and August and October, 1998, respectively). Forecasts based on local observed climatology were the baseline of zero skill. Forecasts of persistence of the initial conditions were the simplest forecasts against which the dynamical model forecasts were compared. Figure 3 (Di Lorenzo et al., 2002, in preparation) shows some results that are very encouraging. The model dynamic forecasts are able to beat persistence for both surveys. The relative importance of initial conditions to surface atmospheric forcing on forecast skill was also explored. A framework for understanding the limits of predictability in this context during different times of the year and in nearshore and deep ocean regions is outlined in Figure 4 (Di Lorenzo et al., 2002, in preparation).

3.5 Tests of the Ecological Models

We have incorporated a variety of different NPZD-type ecosystem model formulations into ROMS (Miller et al., 2000). These models consist of several (usually 5-7) biological "tracers" which are advected and mixed by the ROMS transport scheme. In addition, these tracers undergo vertical motions, either by particle sinking or specified behavior, and they interact with each other in an ecosystem/biogeochemical context. The modularity of the ROMS code allows us to configure different model types (Fasham et al. 1990; Moisan and Hoffmann 1996a,b; Hood et al. 2001).

3D Ecosystem Model Tests: The biological fields are strongly influenced by 3D physical variations. Therefore, once a physics fit is obtained, it can be used to drive the ecosystem model. The best sampled CalCOFI period after SeaWiFS began is February 1998 (Cruise 9802), so we commenced testing the 4D ecosystem model for that period.

We first sought to understand how sensitive the ecosystem model is to the various terms that influence it. Ecosystem variations can take the form of intrinsic biological variations (oscillations, aperiodic behavior, chaotic behavior) or physically forced variations, or a combination of the two. We recognized that if a nonlinear ecosystem model generates its own time-dependent variations (with steady or seasonal cycle forcing) when only very limited data is available to validate a model, then we would never be able to distinguish intrinsic biological variations from physically forced ones. Hence, we began to ask the question 'What fraction of the variance of the biological observations can be explained by an ecosystem model that is dominated by physically forced biological variations?'

We pursued this line of research by choosing biological coupling parameters that allow the ecosystem model to reach a quasi-steady state in the presense of fixed (in time) physical forcing. (Note that the forcing can include steady upwelling, steady advection, etc.) Starting with the 7-component NPZD model, we held the model physical initial fixed for (typically) 90-day runs and allowed the ecosystem to approximately equilibrate to this forcing. Initial test yielded wavelike structure in the biology (periods near 30 days) that could be extinguished by including stronger damping (death or grazing). Once the biology was quasi-equilibrated to the initial condition of the physics, the entire physical-biological system was allowed to evolve freely over the during of the Feb 1998 CalCOFI to determine if the character of the response was similar to observations of SeaWiFS chl-a and CalCOFI sub-surface observations.

Examination of the SeaWiFS record for the February 1998 timeframe reveals a persistent chl-a signature in the coastal waters. In animations of SeaWiFS imagery, the coastal chl-a field remains high along the coast (even during this downwelling period during El Niño) and has small signals offshore. The model version of that yielded enhanced chl-a near the coast (like the observed) but large values offshore (not observed) around upwelling fronts (Figure 4, taken from Di Lorenzo et al., 2001). Correcting this inadequacy has been the main focus of our recent research.

We have explored the use of simpler ecosystem models (e.g., 2-component NP, 3-component NPZ, etc.) in the 3D time-dependent evolution of the Feb 1998 model of CalCOFI. We have not yet reached the point where we feel that the results are qualitatively similar to observations to a sufficient level that quantitative estimates of model-data mismatch can be computed and reduced by inverse solutions. Our goal is to use the data assimilation procedure to modify the ecosystem parameter set to achieve a best fit model solution over a specific CalCOFI cruise period.

We also have constructed a more complicated ecosystem model that includes carbon and oxygen budgets. In order to resolve the time variations of the 3 components of the dissolved inorganic carbon ([DIC]) pool, the model required the addition of [DIC] and alkalinity ([Alk]) pools. With these two components the remaining 3 components of the carbon cycle, [CO_2], [HCO_3^-], and [CO_3^{2-}] are calculated. We are presently using a version of the CO2SYS.EXE code to solve the equation of state of the CO_2 system (Lewis and Wallace, 1999). With this addition, it was also necessary to add in required DOC and POC pools so that we could track to stoichiometric balances.

1D Ecosystem Model Performance: Because many of the parameters in the ecosystem model are poorly known, we have investigated the model sensitivity over a wide range of parameter sets. Our approach has been to use a one-dimensional (1D) mixed-layer model that has been coupled to the ecosystem model. By reducing the ecosystem model testing to a 1D problem we are able to investigate the ecosystem model's sensitivity to variations in the parameters. The model is being tuned to the two CalCOFI regions (coastal and offshore) by comparing the model results against climatological profiles of temperature, density, NO_3, chl-a and O_2 that were obtained from the CalCOFI dataset. The comparison between the model results and the data are used to make subjective changes in the parameter set. An example of one such comparison (Figure 5) demonstrates that the 1D model is capable of resolving several of the observed features (Miller et al., 2000). The mixed layer model is capable of resolving the seasonally varying SST and mixed-layer depths. The nitracline is well established at about 100-150 m, with very low concentrations at the surface. Surface chl-a is highest in the winter with an established chl-a maximum at about 80-90 m. Unfortunately, the chl-a climatologies had to be averaged over 2 months in order to achieve a smoothly varying chl-a field. One issue that has yet to be resolved is why the model creates such a thin chl-a maximum at depth while the data suggest a wider feature. Part of this discrepancy may be due to the averaging of many data profiles to obtain the climatologies of the dataset, another may be to due unresolved phytoplankton community structure which could impart a layering effect within the chlorophyll maximum layer. Oxygen profiles from the model compare well with the climatologies and show a gradual decline in oxygen levels with depth and a sub-mixed-layer oxygen maximum during the summer which is brought about by summer subsurface oxygen production.

4. Significance and Implications

Studies of the CCS which lead to predictive capabilities are important for many practical problems, including fisheries biology and tracking pollution spills. We expect to eventually develop the first predictive model of the CCS in the CalCOFI region which can be initialized with hydrographic, ADCP, and T/P data. Our dynamical analyses of the evolving model flows has helped to answer the longstanding questions concerning the physics controlling CCS variations on the time and space scales resolved by the CalCOFI and T/P data and their concomitant influence on ecosystem variations. NASA satellite data was used to develop initial conditions, validate the model results, and provide forcing fields.

This project was seminal in our developing a capability to model circulation and ecosystem response in the CCS. The tremendous interest in this research as expressed by colleagues around the world has resulted in our becoming involved in several related projects that would not have been initiated without this initial funding by NASA. Under ONR funding, Miller and Cornuelle (with Dr. Arango of Rutgers and Prof. Moore of U. Colorado) are building the tangent linear and adjoint model for ROMS and testing it in the CCS region (compared with the Green's functions technique used here). NASA funding for "Ocean Carbon Flux, Transport, and Burial Within the Western and Eastern U.S. Coastal Zones" involves Miller and Cornuelle adjusting large-scale forcing of the UCLA version of the CCS model (from Baja to Washington, 0-2000km offshore) to improve its match to seasonal cycle eddy statistics and Moisan building and testing the carbon components of the biogeochemical model for both coasts. Miller and Cornuelle are funded by NOAA under a grant entitled "North Pacific Climate Variability and Steller Sea Lion Ecology: Retrospective and Modeling Analysis" to study the importance of decadal-scale changes in mesoscale eddy statistics on the ecosystem response in the Gulf of Alaska and its effect on the Steller Sea Lion decline. Chereskin is a PI on CCOAST (California Current Observing and Analysis System Team).

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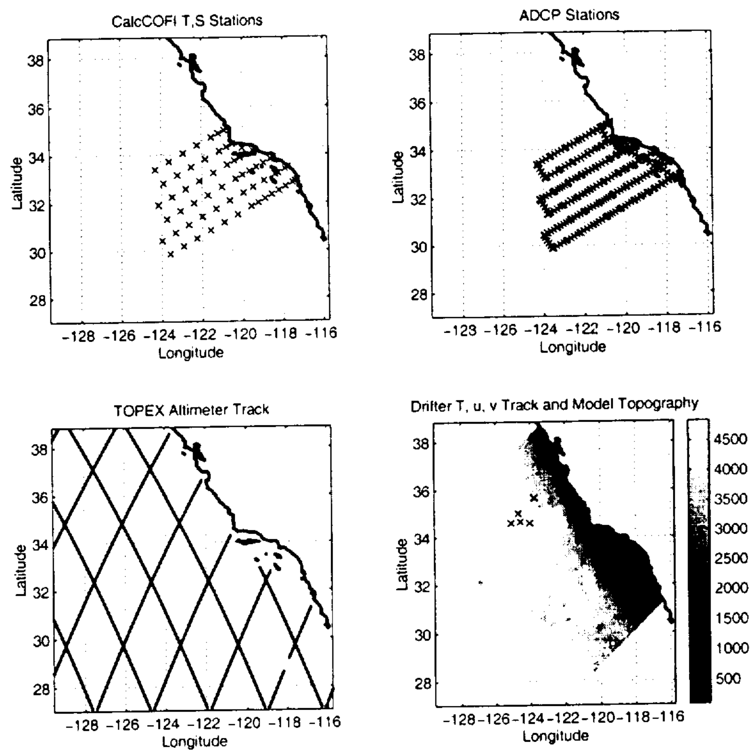

Figure 1. Figure 1. Distribution in space of the data types to be fit by the inverse method in the model domain for July 1997: (a) CalCOFI hydrographic stations of temperature, salinity, nitrate, Chl-a, and bulk zooplankton, (b) ADCP upper-ocean currents, (c) sea-level from TOPEX representing 9-day time differences, and (d) drifter observations of 15m velocity and SST. Also shown as (d) is the bathymetry of the model as shaded contours.

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